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LABORATORY AND FIELD TESTING OF THE M1 LIGHTWEIGHT STEEL TOW BAR SYSTEM

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MECHANICS AND STRUCTURES BRANCH

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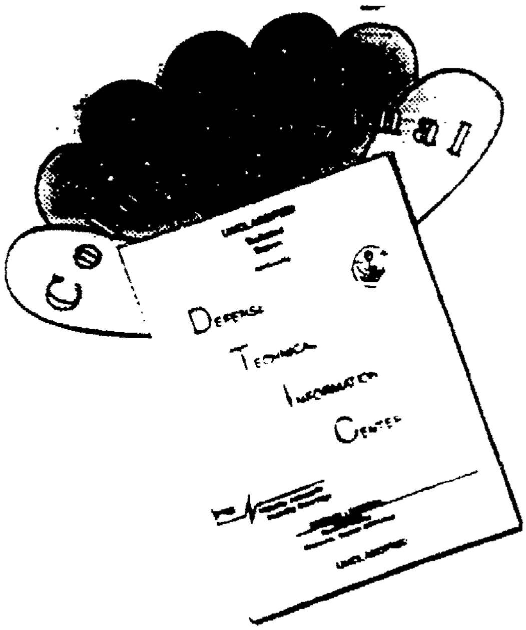

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ABSTRACT

In conjunction with the U.S. Army Tank-Automotive Command (TACOM), the U.S. Army Materials Technology Laboratory (MTL) has developed a lightweight steel tow bar system as an alternative to the current system used in the recovery of M1 Main Battle Tanks. The advantages of the new tow bar system are an increase in strength (by 30%), lighter weight (23% weight savings), and interchangeable legs.

A series of instrumented laboratory and field tests were conducted in order to evaluate the structural integrity of this new steel tow bar system. The laboratory tests were performed in a 600,000-lb capacity tension/compression test machine at MTL. The field tests were conducted on the Perryman and Churchville Test Courses at Aberdeen Proving Ground, Aberdeen, MD.

Prior to and following all tests each tow bar leg was examined for structural integrity using X-ray radiography. This nondestructive evaluation method was used to verify the success of weld penetration and identify any areas where cracks may have been induced as a result of welding or testing.

CONTENTS

INTRODUCTION

The current tow bar system utilized in the recovery of M1 Main Battle Tanks is categorized as a size III, type V, heavy duty tow bar system (see Figure 1) and was designed in the 1950's for use in the recovery of M60 battle tanks. It is constructed of 4130 steel, weighs 340 pounds, and requires four to five soldiers for installation. Having been designed to recover the M60 at 54 tons, the towing capabilities of this tow bar system was surpassed by the requirement to tow the much heavier M1A1s or M1A2s at 70 tons each. The increased weight of these vehicles has pushed the current tow bar system beyond its design limitations.

The new tow bar system is constructed of both 4130 and 4340 alloy steels (see Figure 2) and possesses several key advantages over the current system. These include an increase in strength of 30% for towing 70-ton M1A1s and M1A2s, a weight reduction of 23% (the new system weights 260 lbs) resulting in easier installation and identical interchangeable legs (both of which connect to a separate lunette, as shown in Figure 3). The leg interchangeability feature allows for component replacement in the field if a failure were to occur. Currently, damaged steel tow bars require total replacement.

Instrumented laboratory and field tests were conducted to evaluate the structural integrity of the new tow bar system. The laboratory tests were accomplished at the U.S. Army Materials Technology Laboratory (MTL). The field tests were conducted on the Perryman and Churchville Test Courses at Aberdeen Proving Ground (APG) in Aberdeen, MD.

TEST PROCEDURES

Laboratory Tests

A series of instrumented tension and compression tests were performed to verify the strength of an individual leg of the new tow bar. Towing requires that each leg be able to sustain a maximum load of 240,000 lbs (working load). This load magnitude was previously determined (theoretically[1] and proven experimentally[2] through field tests) to be the maximum force sustained during the towing operation of a 70-ton M1A1. However, in order to meet the design requirement of a 1.5 factor of safety (design requirement from U.S. Army Tank-Automotive Command), the maximum load sustained before yielding occurs was to be 360,000 lbs per leg (50% more than 240,000 lbs). Therefore, the goal of the static tension and compression tests was to achieve a maximum load of 360,000 lbs (design load) without yielding.

In addition to proving the strength of the design, the results obtained from these tests served an alternate purpose. During field testing, the data recorded was in units of micro-strain (mstrain) and there was no manner by which the load applied could be monitored during these tests. The results of the lab tests provided a database to which the field test data could be compared. From this comparison, the magnitude of load applied during field testing could be approximated by matching corresponding strain values for strain gages located at the same points on the legs for both types of tests.

1. CAMPBELL, T., and SAMAVEDAM, G. *Advanced Composite Tow Bars*. Foster-Miller, Inc., Waltham, MA. Prepared for the U.S. Army Materials Technology Laboratory, Contract DAAL04-87-C-0089, May 1990.
2. CUZZUPE, L. P., and BEATTY, J. F. *Field Tests of a Type V, Size 3, Heavy-Duty Tow Bar*. U.S. Army Materials Technology Laboratory, October 1986.

Prior to being placed in the machine, the specimen was examined using X-ray radiography. This nondestructive evaluation method was used to determine if full weld penetration was achieved and whether there were any inherent cracks or flaws present as a result of welding.

The machine used to perform all laboratory tests was a 600,000-lb capacity BLH tension/compression machine (see Figure 4). To monitor the performance of the specimen during these tests, a combination of uniaxial and biaxial strain gages were mounted on the test leg at the locations shown in Figure 5. The uniaxial gages monitored longitudinal (along the tow bar leg) strains while biaxial gages monitored longitudinal and transverse (across the tow bar leg) strains.

Field Tests

Following the successful completion of the laboratory tests, an additional five tow bar legs were fabricated. Each of these legs was then X-rayed and laboratory tested in tension to the maximum load of 360,000 lbs as a proof test prior to field testing.

Field testing of the tow bars was conducted at APG and was performed at two separate test areas, Perryman and Churchville. Perryman Course 3, categorized as being a rough course, subjected the tow bar to the combined rolling motions of both vehicles. This course simulated the motion of the tanks as it would be if the vehicles were passing over berms and gullies. Perryman Course 4, which is categorized as a severe course with the presence of mud holes and natural marshland, subjected the tow bar to a substantial amount of impact abuse.

At the Churchville site, Course "B" was used during all of the cross-country tests performed. This course was categorized as moderate to rough native soil and stone, ranging from muddy to dusty, depending upon the weather. Grades as steep as 29% were also present on this course.

Two towing vehicle configurations were utilized during field tests at both sites. The first configuration was an M88A1 (weighing 58 tons) towing an upweighted M1A1 (weighing 70 tons, see Figure 6), and the second configuration was an upweighted M1A1 towing another upweighted M1A1 (weighing 70 tons each, see Figure 7). Upweighted M1A1s refer to 60-ton test vehicles which were modified by adding extra weight to simulate the actual 70-ton M1A1s. The original M1A1s were only 60-ton vehicles.

Prior to testing, the tow bar was instrumented with uniaxial strain gages (refer to Figure 8 for strain gage locations). During all instrumented field tests, the same tow bar system was used for all tow tests. In addition to the strain gages, each leg was instrumented with three type K thermocouples just prior to the start of all M1A1-M1A1 towing. The thermocouples were used to monitor the temperature change of the tow bar during towing as a result of the M1A1's exhaust bearing on it. Two extra thermocouples were also installed prior to testing; one on the bottom side of the bustle rack of the towed M1A1, and the other on the exhaust grill of the towing M1A1 (see Figure 9 for all thermocouple locations). The purpose of these two thermocouples was to record the maximum temperatures achieved at the bustle rack and the exhaust grill during towing. These temperatures were recorded for purely informational reasons. The bustle rack is often used for storage and during towing is exposed to exhaust heat. Thermocouples were not required during M88A1-M1A1 towing because the M88A1 was equipped with an exhaust deflector that directed the exhaust upwards away from the tow bar.

The data acquisition system used to record strain and temperature information was the MEGADAC 2000 which was programmed to store data at a rate of 200 samples/second/channel. With the use of a static inverter, the data acquisition system was powered directly from the electrical power of the towing vehicle (a 24V, DC power source). In addition, a video camera was mounted on the towed vehicle to record all action of the tow bar during testing.

The first three tests utilized the M88A1 recovery vehicle (58 tons) towing an upweighted M1A1 (70 tons) at the Perryman Test Area. During test 1 at Course 3, the M1A1 was towed for one full lap (3.3 miles) at a speed of 5 mph to 10 mph with a fully instrumented tow bar. Upon the completion of the single lap, the test was halted and the data was inspected to ensure that all equipment was performing properly.

Following the data inspection, the next test (test 2) was set to begin on Course 4. The M88A1 had difficulty towing the M1A1 about this course versus the last course. On several occasions, the vehicles became mired in mud. During the maneuvers executed to free both vehicles, it was evident that the weight differential and the lack of sufficient power of the M88A1 (750 hp versus 1500 hp for the M1A1) hampered the recovery of the M1A1.

Upon completion of this lap, the equipment was inspected and a second lap on this course was run (test 3) utilizing this configuration. Each lap on Perryman Course 4 was 2.5 miles in length.

After the completion of these three tests, the M88A1 was replaced with another upweighted M1A1. This was the second towing configuration previously mentioned. All test equipment was transferred to the towing M1A1 and installed in the same manner used on the M88A1. Also, the M1A1-M1A1 tow configuration required that thermocouples be installed prior to the start of the next test.

Once the equipment was ready, the two M1A1s proceeded onto Perryman Test Course 3 to execute test 4. Utilizing this tow configuration, the towing M1A1 pulled the "disabled" M1A1 with ease (due to equal weights and increased horsepower (over the M88A1) - 1500 hp) about this course for one full lap.

Testing then continued on to Perryman Test Course 4. During this test (test 5), the tow bar was subjected to its greatest abuse. On several occasions, the towed vehicle was mired and the only manner by which to free the vehicle was to back up to it, forcing the tow bar to assume a near vertical position by lifting the rear of the towing vehicle, and allow the towing vehicle to get a running start. Upon reaching its normal horizontal position, the tow bar was exposed to significant amounts of impact loading.

Upon the completion of one full lap, field testing at the Perryman Test Area was concluded and the M88A1 and the two M1A1s were transported to the Churchville Test Area.

The first towing configuration utilized at Churchville was the M88A1 towing the upweighted M1A1. Again, all the data acquisition equipment was installed in the M88A1 and powered by the vehicle's electrical system. The strain gage locations were the same as those used on the previous tests conducted at the Perryman Test Area (see Figure 8).

At the start of this test (test 6), it was evident that the M88A1 was experiencing difficulties while towing the heavier M1A1 uphill. On numerous uphill tows, speeds decreased to 1 mph, and on downhill the heavier M1A1 could be felt pushing the lighter M88A1. At the end of this test, due to the terrain of the course and the relatively low power of the M88A1, it was decided that, for personnel safety and to avoid jackknifing, all of the remaining four tests would be conducted utilizing the M1A1-M1A1 configuration. Therefore, all data acquisition equipment was transferred to the towing M1A1.

Prior to beginning test 7, with the M1A1-M1A1 configuration, thermocouples were again installed, as previously shown in Figure 9, and all data acquisition equipment and sensors inspected for performance. The two M1A1s then proceeded onto Churchville Course B. From the beginning of this test, it was obvious that the M1A1 towing the "disabled" vehicle was able to maintain traction and was suitably powered to tow the "disabled" vehicle. During this test speeds ranged from 2 mph to 23 mph. Following the successful completion of one full lap, all equipment and the tow bar were inspected for proper operation and damage, respectively.

After some data reduction and the confirmation that all sensors were functioning properly, this towing configuration performed another lap on Course B (test 8). Speeds remained in the range of 2 mph to 23 mph.

After completing test 8, the driver of the towing vehicle was then instructed to drive as fast as possible (safely) around the course for an additional two laps. These last two laps simulated extreme service use (tests 9 and 10).

In order to simulate true field conditions, the last task performed was a structural integrity test to determine if the bar could withstand the track pressure of an M1A1. In the parking area outside of the Churchville shop, one of the field-tested tow bar legs was placed on the pavement and run over with an M1A1. In addition, the female end of that same tow bar leg was run over so as to assure that if this were to happen in the field, the end fitting would not fail. Such an occurrence would render that leg useless.

RESULTS

Laboratory Tests

Before the laboratory tests, the prototype test leg was inspected using X-ray radiography. This inspection showed that there were no flaws present in the leg and that full penetration of the welds was achieved. Once inspection was passed, the tube was placed in the test machine and the lab tests were performed.

Table 1 summarizes the static cycles performed on a single tow bar leg and shows that there were two pin configurations by which the tow bar leg was loaded. The female end fitting has two pins by which it can be fastened to the lunette. When the tow bar is in service (utilizing two tow bar legs), one female end fitting has one pin installed and the female end fitting of the other leg has two pins installed. The dual pin installation locks the lunette in place with respect to one of the tow bar legs. The dual pins keep the lunette from rotating in its own plane during tank recovery maneuvers (see Figure 10 for an illustration). Because the tow bar assembly utilized both pin configurations, it was essential that both be tested.

Table 1. SUMMARY OF STATIC LOAD CYCLES PERFORMED ON A SINGLE TOW BAR LEG

Cycle #	Max. Load/Direction		Pin Configuration
1	240,000 (lbs)	(T)*	Dual Pins
2	356,600	(T)	Dual Pins
3	360,920	(T)	Dual Pins
4	240,960	(T)	Single Pins
5	360,420	(T)	Single Pins
6	240,340	(C)†	Dual Pins
7	360,260	(C)	Dual Pins

*Tension
†Compression

The only failure to occur during any of the test cycles occurred during cycle #2 at a load of 356,600 lbs. The loading pin which was used in the male end fitting fractured. This pin was not a component of the new tow bar system that would be used in service, but was a loading pin used specifically for this test machine.

Table 2 lists the maximum strains experienced by the bar for each test cycle and the strain gage by which it was recorded. Refer to Figure 5 for strain gage locations.

Table 2. SUMMARY OF MAXIMUM STRAINS AND CORRESPONDING GAGE NUMBERS

Cycle #	Maximum Strain	Gage #
1	5138 mstrain	24
2	5606	24
3	4212	23
4	4538	21
5	5263	23
6	-4237	4
7	-4422	16

The yield criteria for the two materials used in the construction of the tow bar were as follows. For the 4340 steel end fittings, the yield stress was 177 ksi[3] and the corresponding yield strain was 6000 mstrain. The tubes were fabricated from 4130 steel alloy with a yield stress of 152 ksi[3] and a corresponding yield strain of 5067 mstrain. During all of the cycles, none of the strain gages exceeded the yield criteria of the materials.

With the exception of cycles #6 and #7, the maximum strains for each test occurred on the female end fitting. As shown in Figure 5, gage #21, #23, and #24 were located about the pinhole areas of the female end fitting. For cycle #6, the maximum strain occurred at gage #4 which was located on the male end of the tube. The maximum strain for cycle #7 occurred at gage #16 which was located on the middle to the tube. Figure 11 shows a typical stress-strain plot generated from the test data by the data acquisition software.

3. American Society for Metals. *Metals Handbook*, 1985.

Following these cycles, the tow bar leg was removed from the test machine and again examined using X-ray radiography. This inspection searched for any cracks which may have developed as a result of the cycles performed. None were detected.

Field Tests

The laps performed during all field tests on the Perryman and Churchville Test Courses are summarized in Table 3 below. Each test represents one full lap on the course listed.

Table 3. SUMMARY OF FIELD TESTS PERFORMED AT THE PERRYMAN AND CHURCHVILLE TEST SITES

Test #	Towing Configuration	Test Course
1	M88A1 - M1A1	Perryman 3
2	M88A1 - M1A1	Perryman 4
3	M88A1 - M1A1	Perryman 4
4	M1A1 - M1A1	Perryman 3
5	M1A1 - M1A1	Perryman 4
6	M88A1 - M1A1	Churchville B
7-10	M1A1 - M1A1	Churchville B

During each of the tests listed (with the exception of tests 9 and 10), the data acquisition system created a number of data files. From each file, plots of strain versus time and temperature versus time (only for M1A1-M1A1 towing) were generated. Figures 12 and 13, respectively, show typical plots produced. Table 4 lists the maximum strains and temperatures encountered during each test listed above.

Table 4. SUMMARY OF MAXIMUM STRAINS AND TEMPERATURES ENCOUNTERED DURING THE TESTS PERFORMED

Test #	Max. Strain	Gage # of Max. Strain	Max. Temp. (°F)	T-couple # Max. Temp.
1	-1279 mstrain	7	---	---
2	913	10	---	---
3	-1280	1	---	---
4	2213	3	681	1
5	2208	3	652	1
6	-1615	6	---	---
7	-1863	4	698	1
8	2414	12	224	5

NOTE: M88A1-M1A1 Test, no temperature data taken.

In addition to the temperature data shown in Table 4, the maximum temperatures of the exhaust grill and the bustle rack were recorded. The temperatures listed in Table 4 were strictly those of the tow bar during testing. For obvious reasons, the maximum temperature recorded was that of thermocouple #7 located at the exhaust grill having a value of 814°F.

Thermocouple #8 which was located on the bottom side of the bustle rack recorded a maximum temperature of 249°F. Both of these maximum temperature values were recorded during test #4.

The final test performed was the structural integrity test. For this test, no instrumentation was used to record data. A 70-ton M1A1 ran over the tube section of one of the tow bar legs already field tested (see Figure 14). In addition, the M1A1 ran over the ends of the female end fitting (see Figure 15). No damage was sustained by either the end fitting or the tube as a result of the track pressure (15 psi to 17 psi) of the M1A1.

Upon return to MTL, all the tow bar legs that were used in the field tests were examined via X-ray radiography. None of the results showed any evidence of cracks or other damage.

CONCLUSIONS

From the laboratory tests performed, it is seen that the new steel tow bar performed precisely as designed. The results showed that the test leg did not yield prior to reaching its design load of 360,000 lbs in tension or compression.

The field tests showed that during recovery operations this tow bar performed far below the design load of 360,000 lbs. There were many instances when the bar experienced dynamic loads that were higher in magnitude and shorter in duration than most of the loading experienced during towing. However, the magnitudes of these dynamic loads only approached the working load of 240,000 lbs.

The maximum strain obtained during all the field tests was 2414 mstrain at gage #12 during test 8. When compared to the strains obtained at the same location during the static tests, this value of strain corresponds to a maximum load of approximately 229,000 lbs encountered during towing.

In addition to the strain data, the temperatures recorded indicate that the maximum temperatures achieved by the tow bar, bustle rack, and the exhaust grill were 698°F, 249°F, and 814°F, respectively. These temperatures do not hinder the performance of this new tow bar system.

It was found from the X-ray radiography that all welds achieved full penetration and that there were no signs of cracks or other damage induced due to testing.

ACKNOWLEDGMENTS

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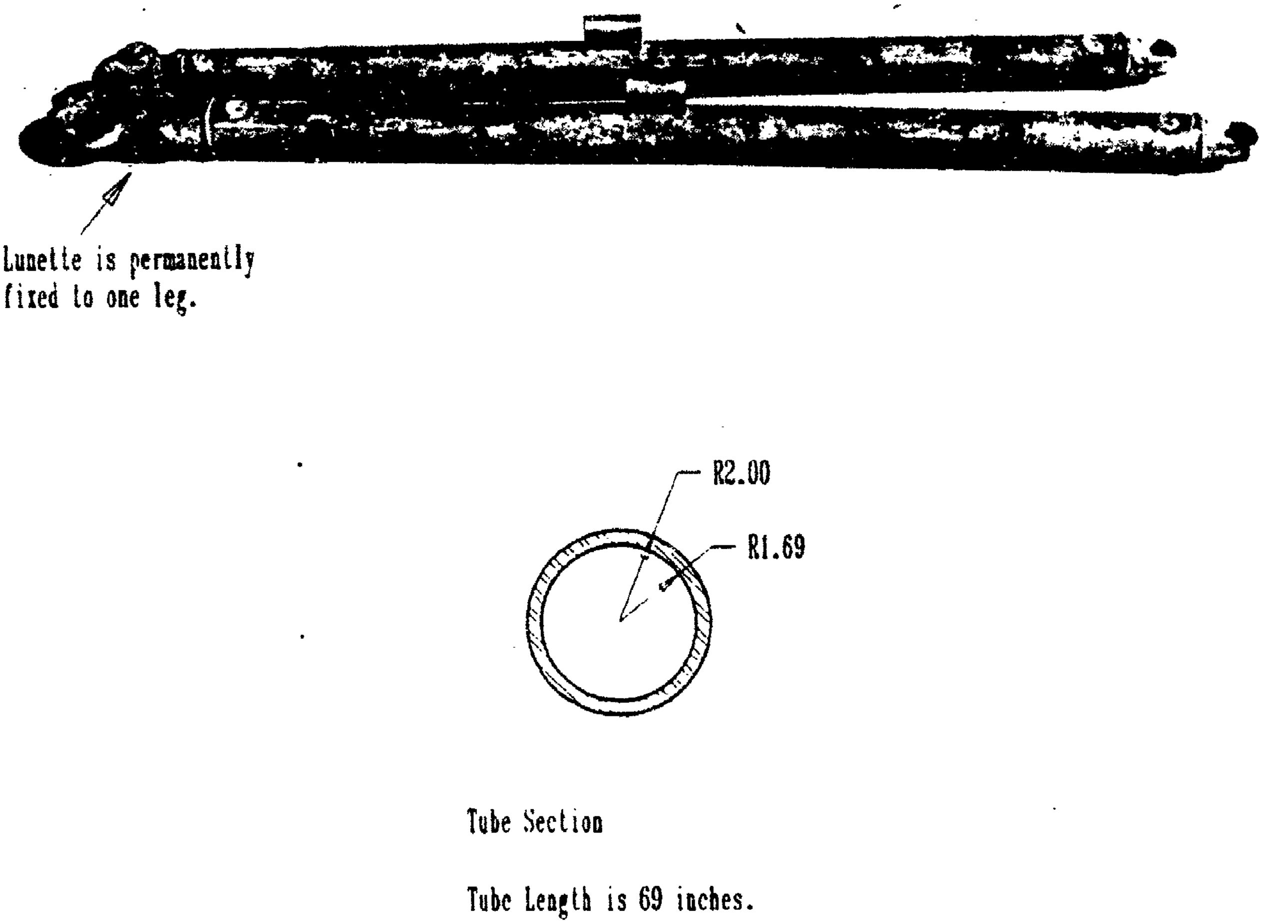

Figure 1. Current tow bar system.

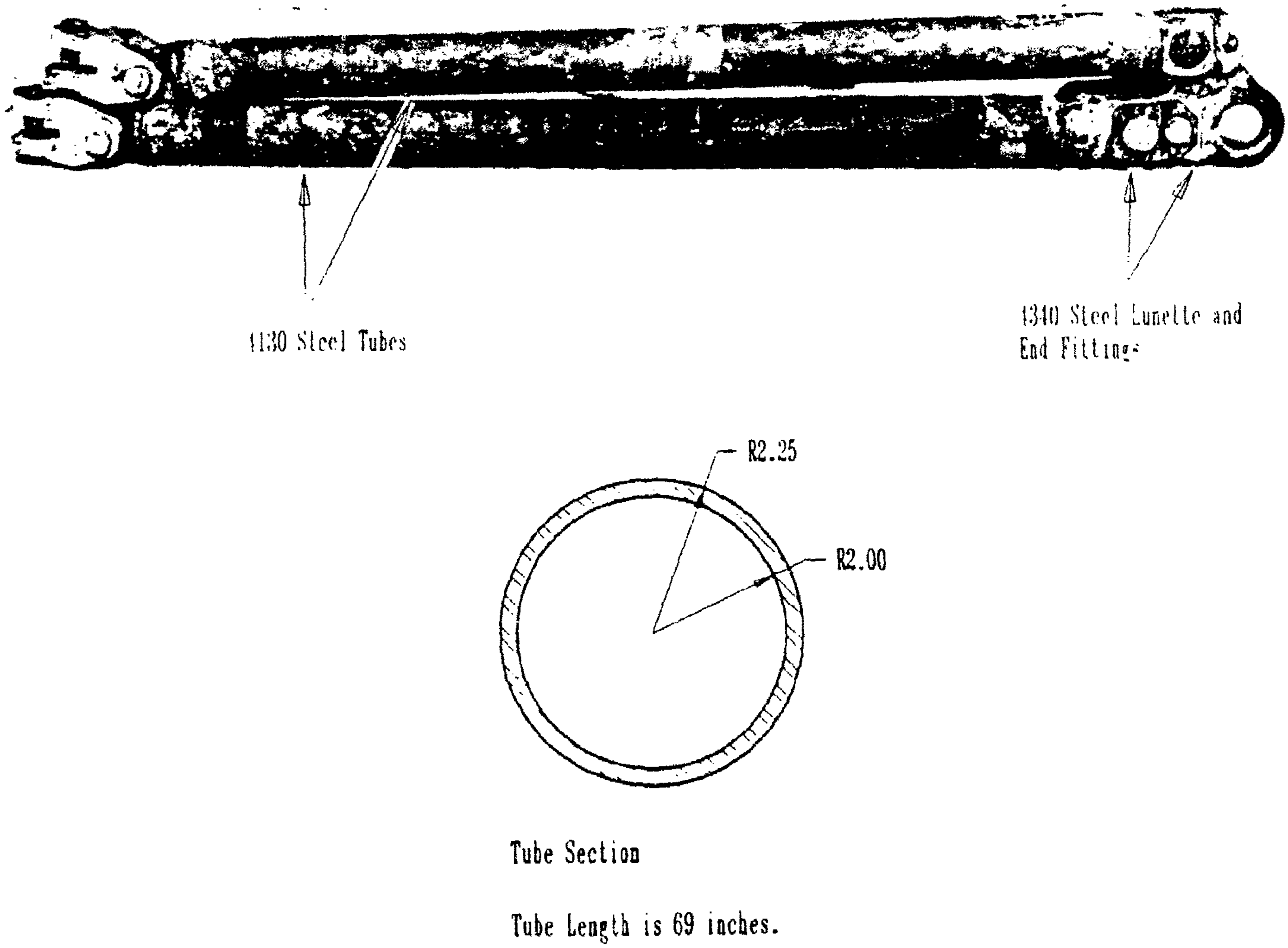

Figure 2. New tow bar system.

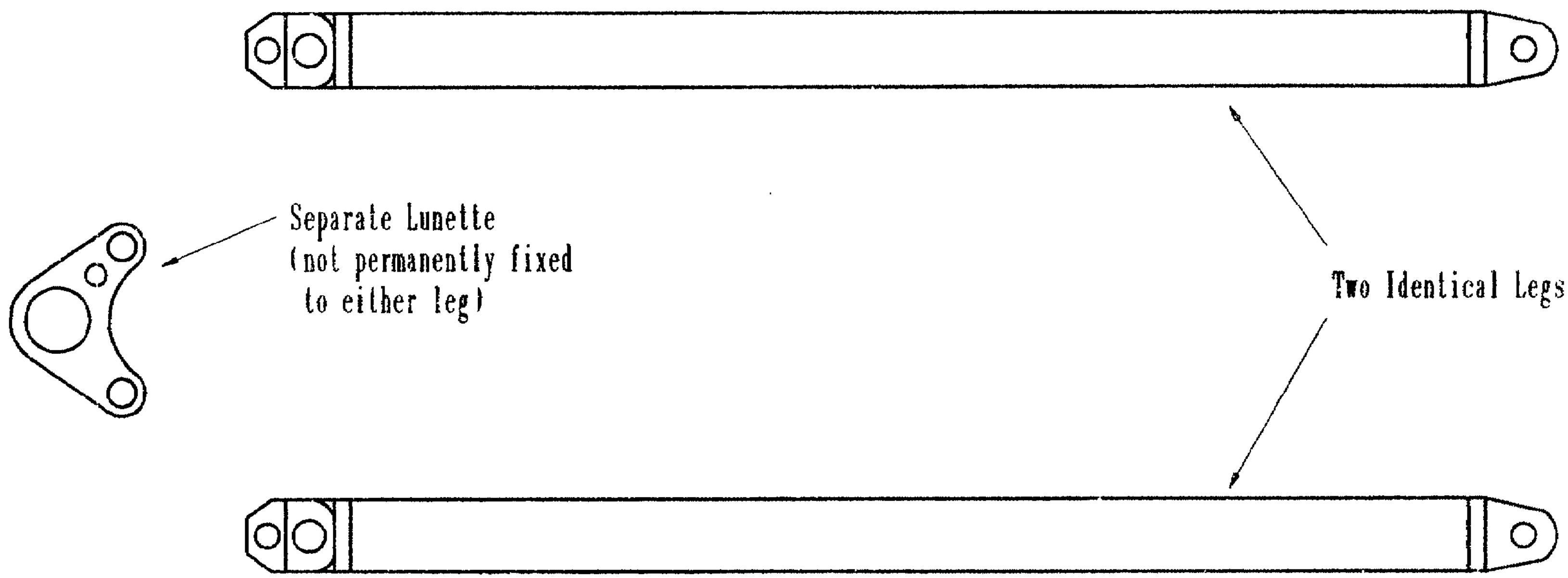

Figure 3. Illustration of identical tow bar legs and separate lunette.

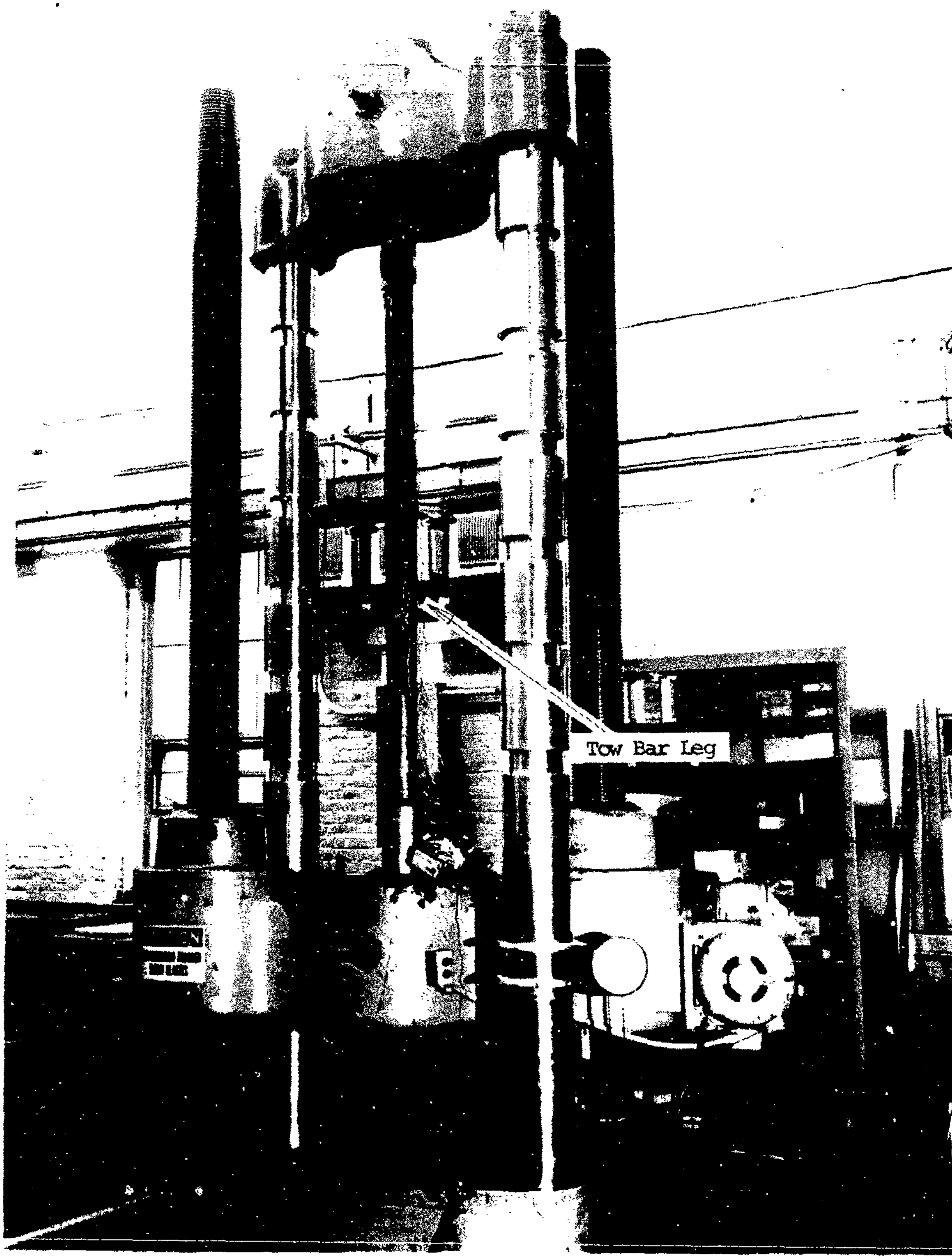

Figure 4. 600,000-lb capacity tension/compression test machine.

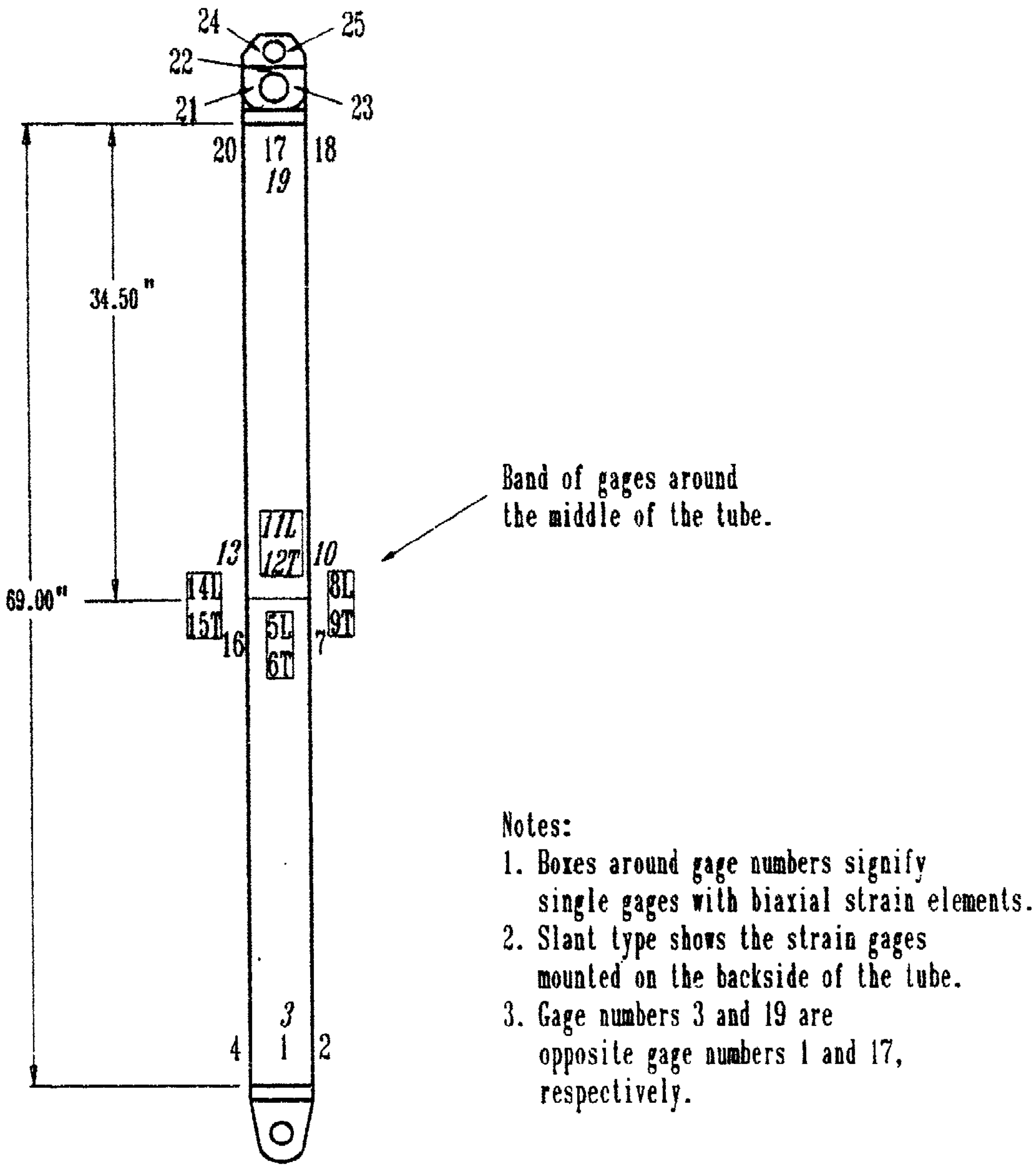

Figure 5. Strain gage locations during static tests.

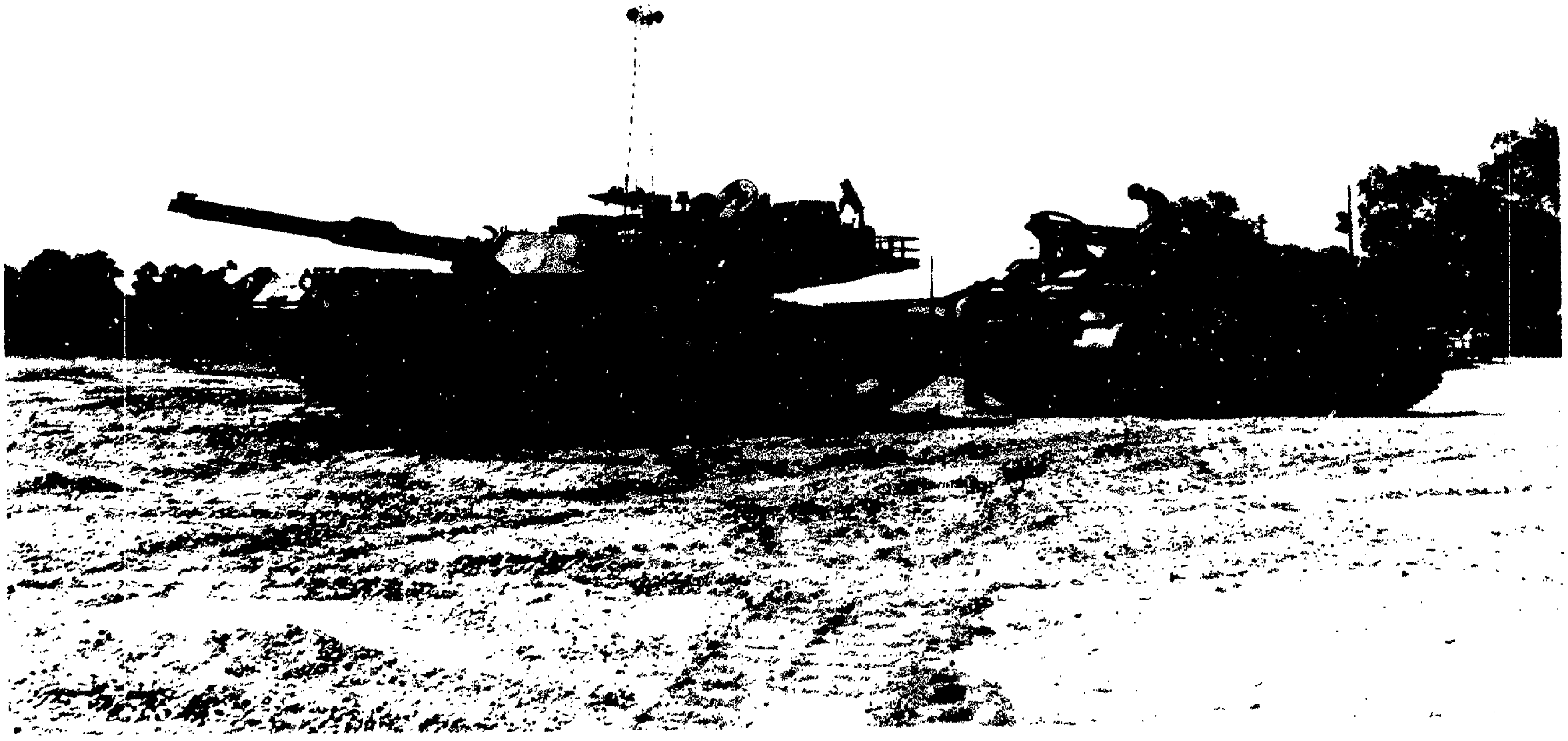

Figure 6. An M88A1 towing and upweighted M1A1.

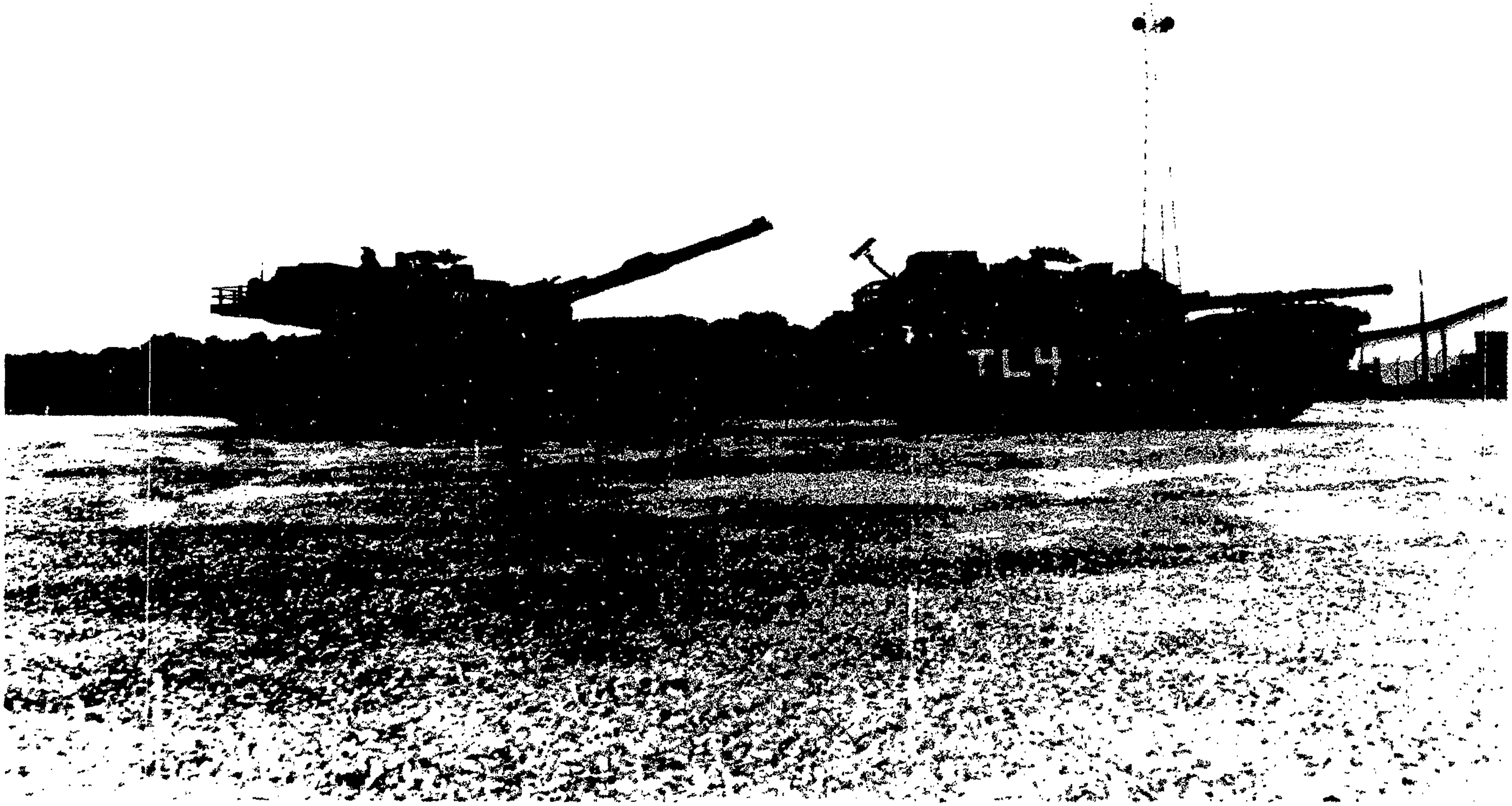

Figure 7. An upweighted M1A1 towing and upweighted M1A1.

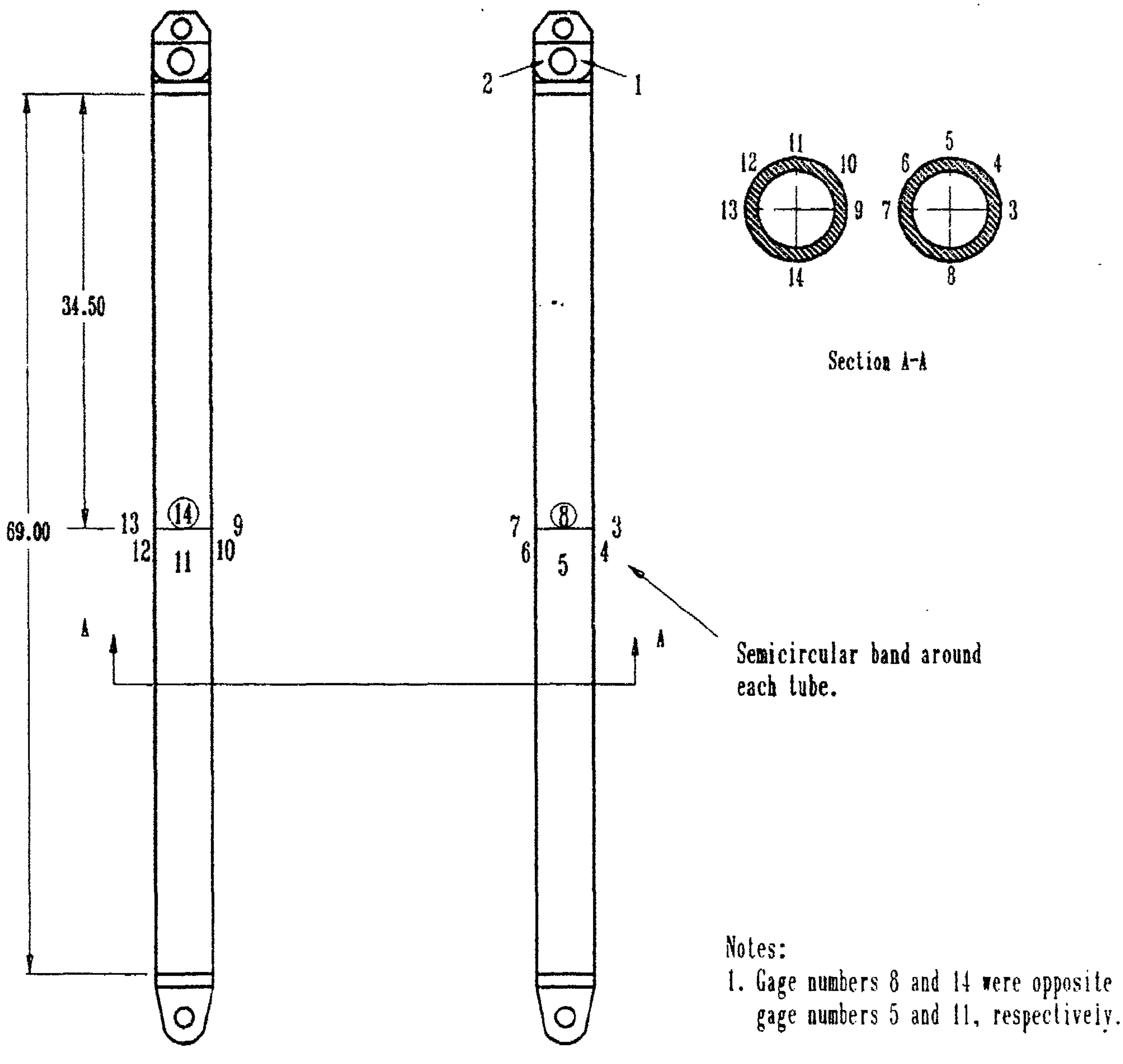

Figure 8. Strain gage locations during field tests.

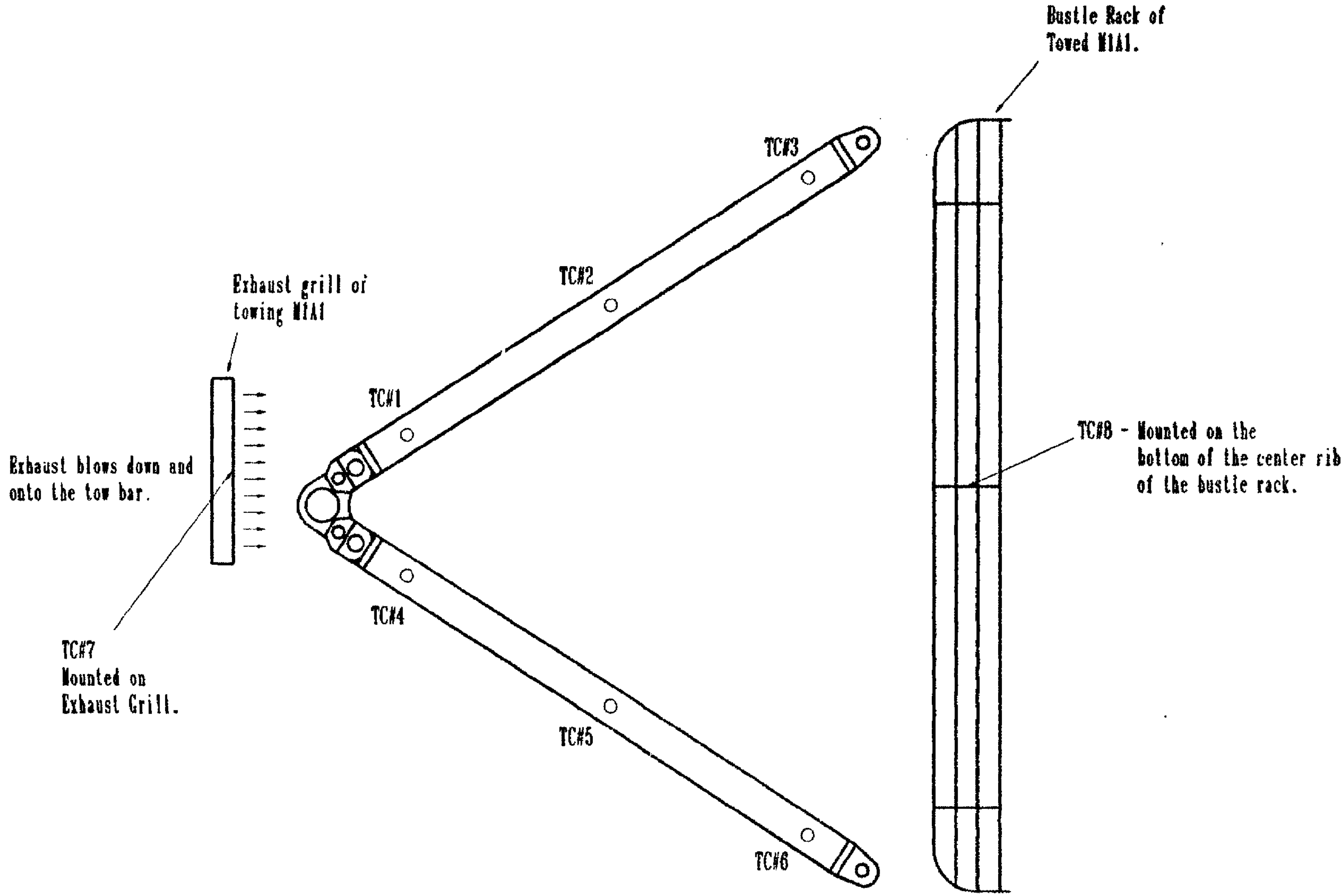

Figure 9. Thermocouple location map.

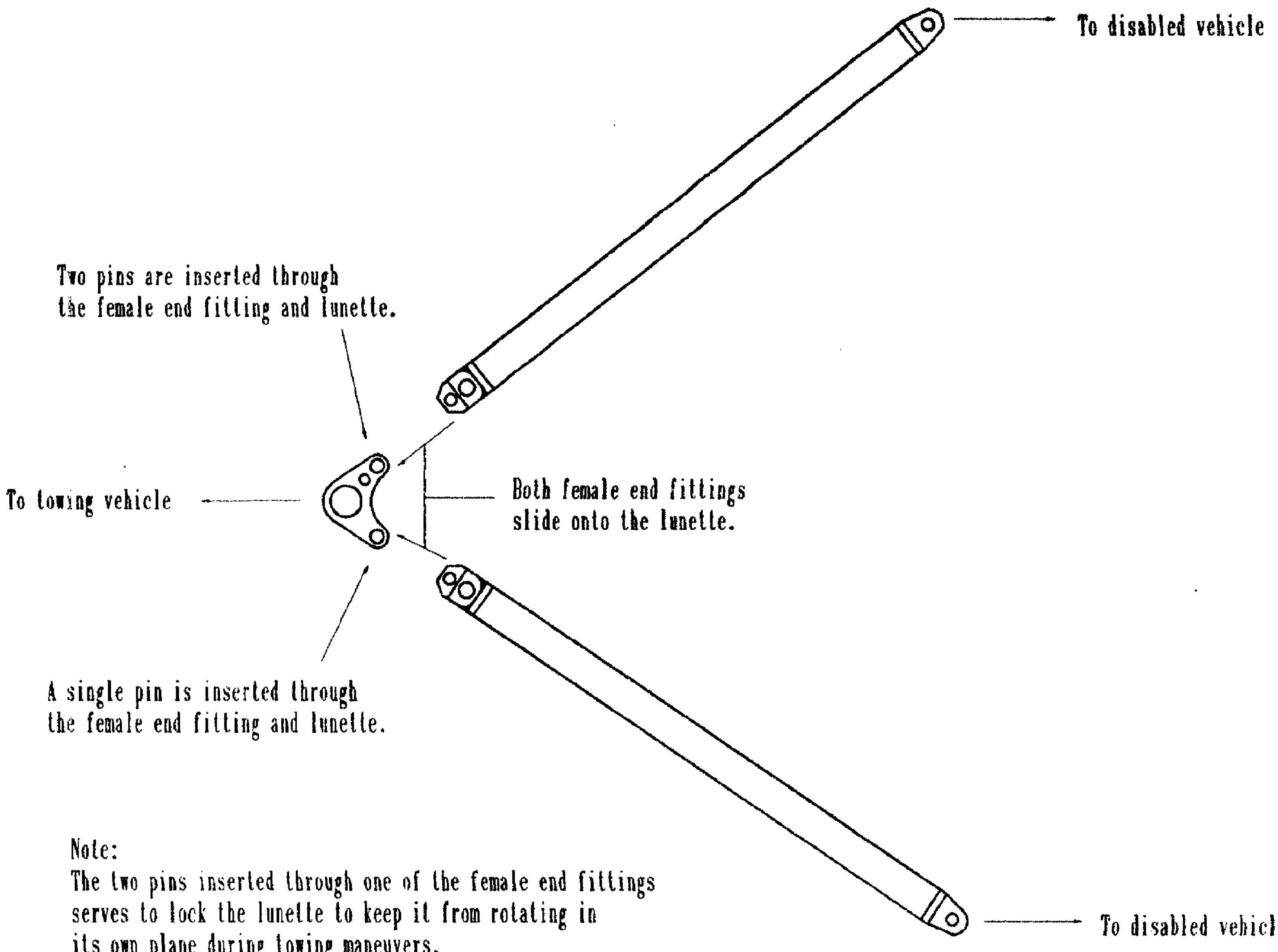

Figure 10. Pins conneting female end fittings to the lunette.

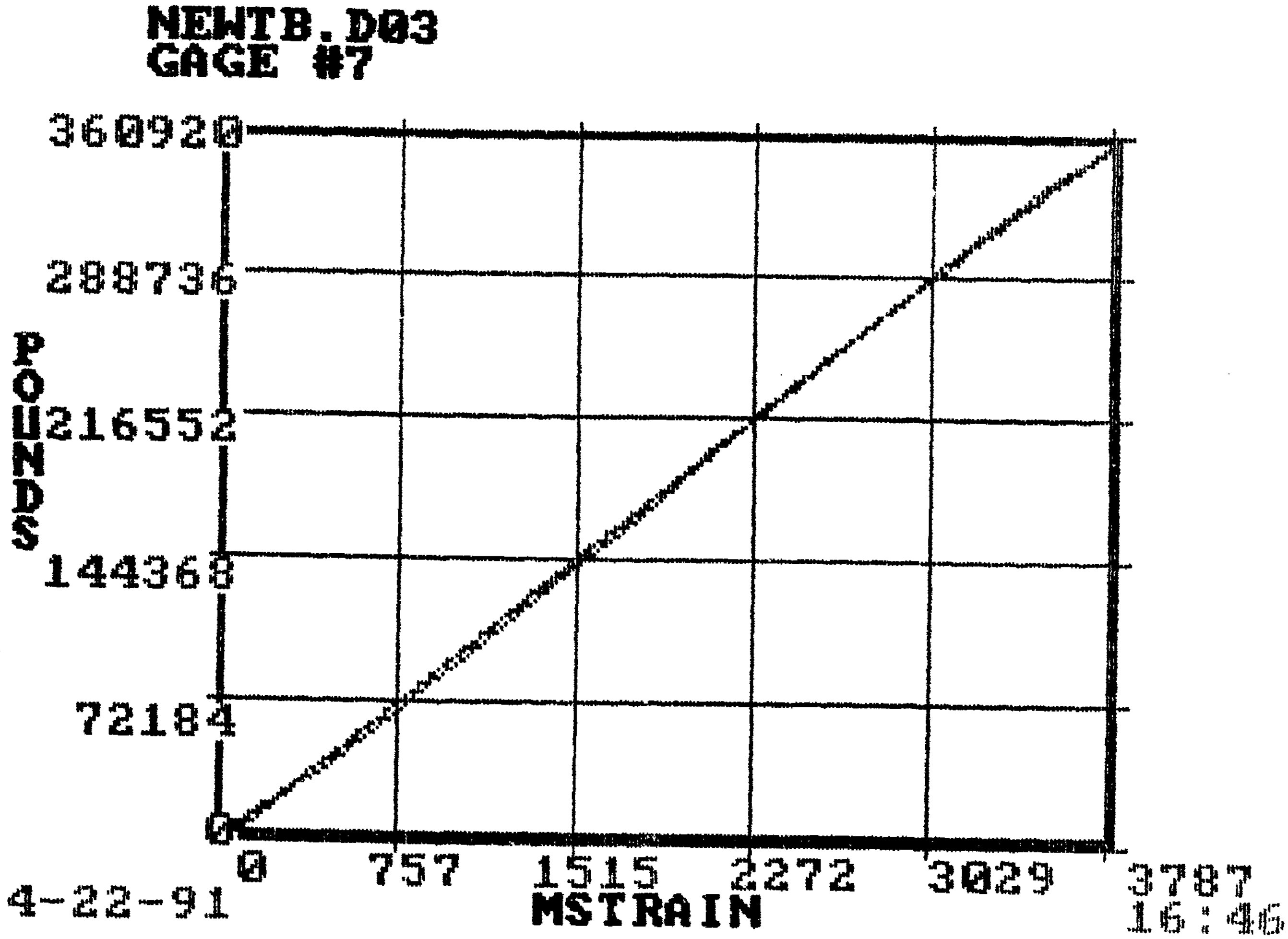

Figure 11. Typical stress-strain plot from static tests.

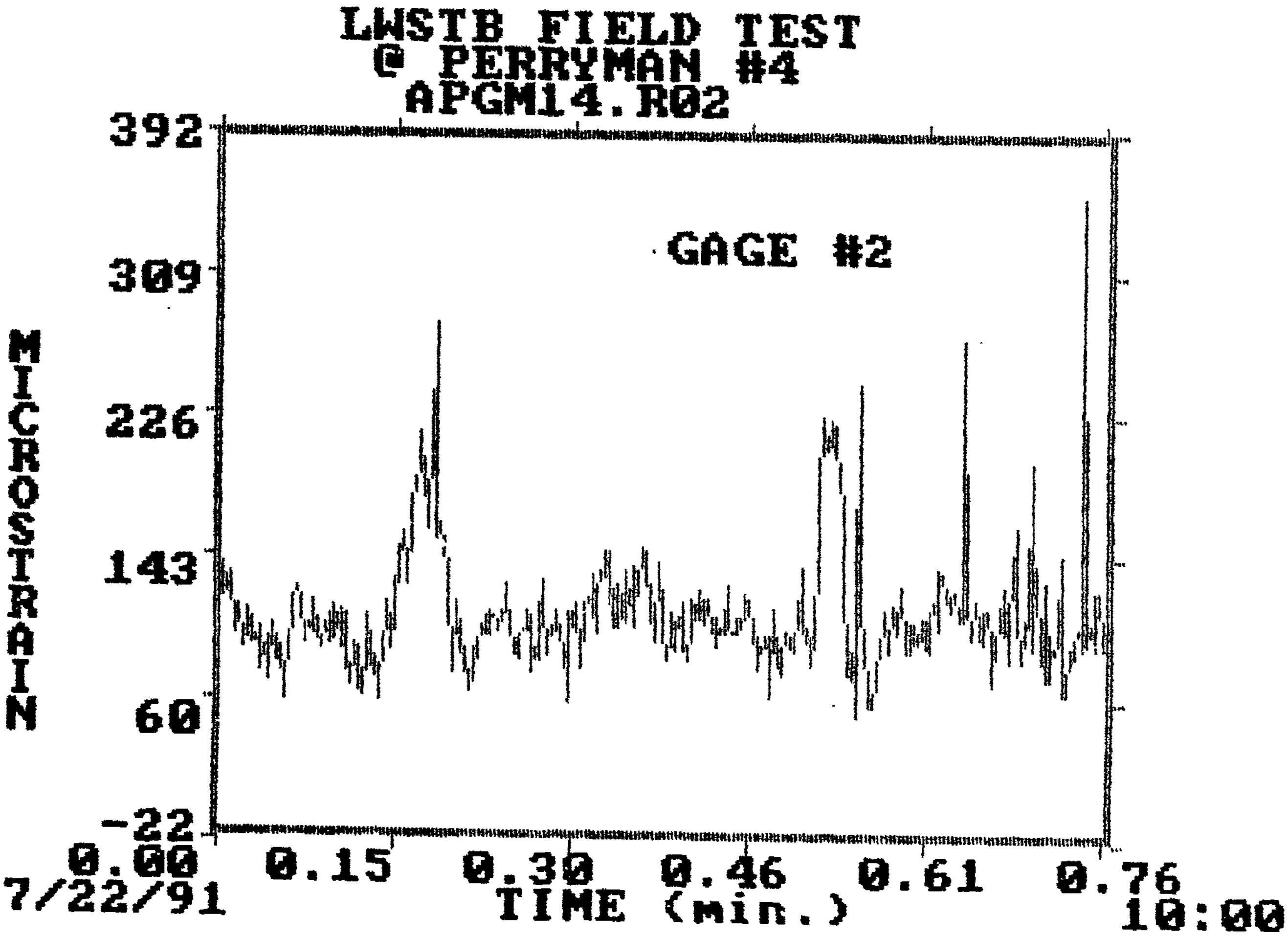

Figure 12. Typical strain plot from field tests.

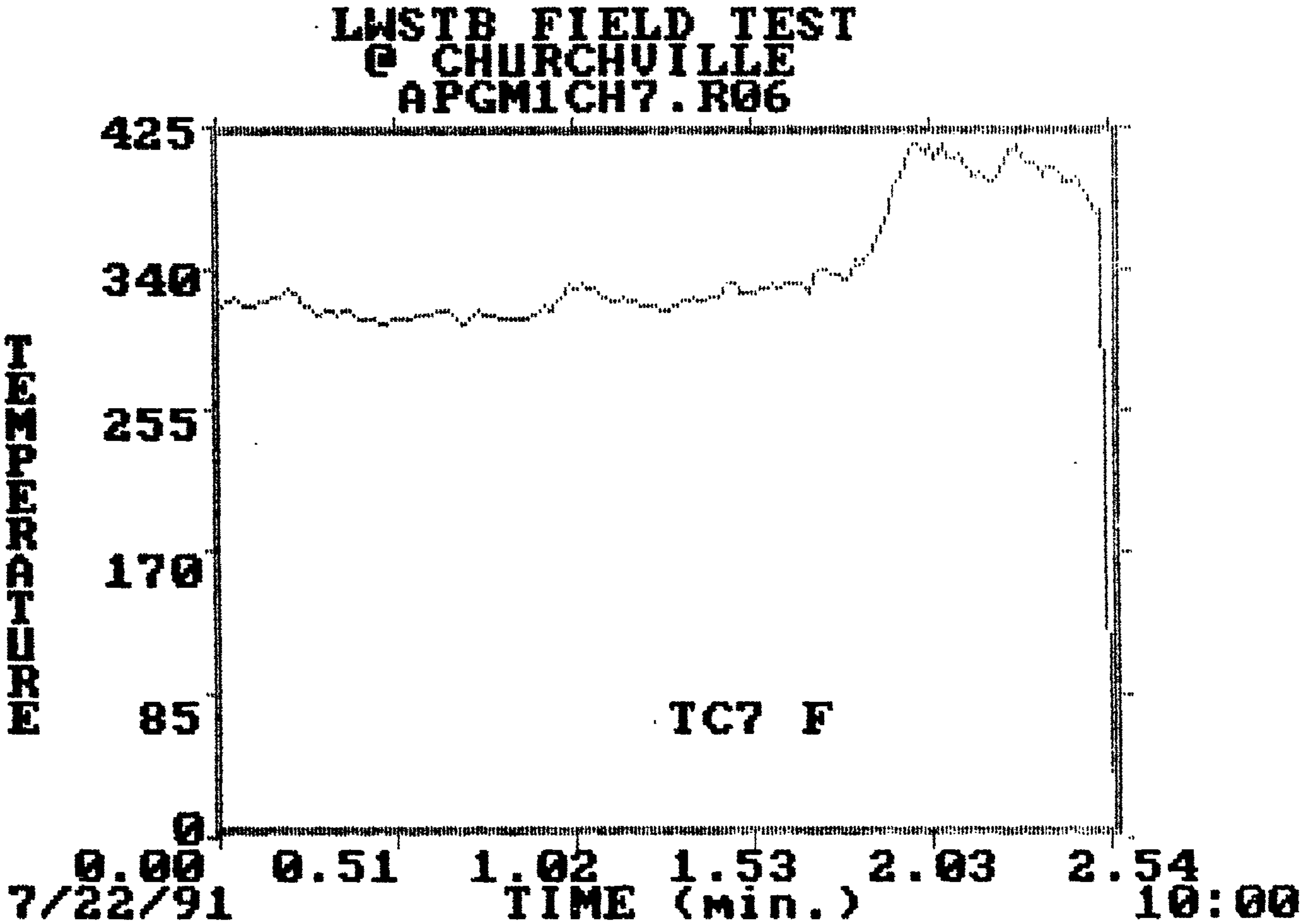

Figure 13. Typical temperature plot from field tests.

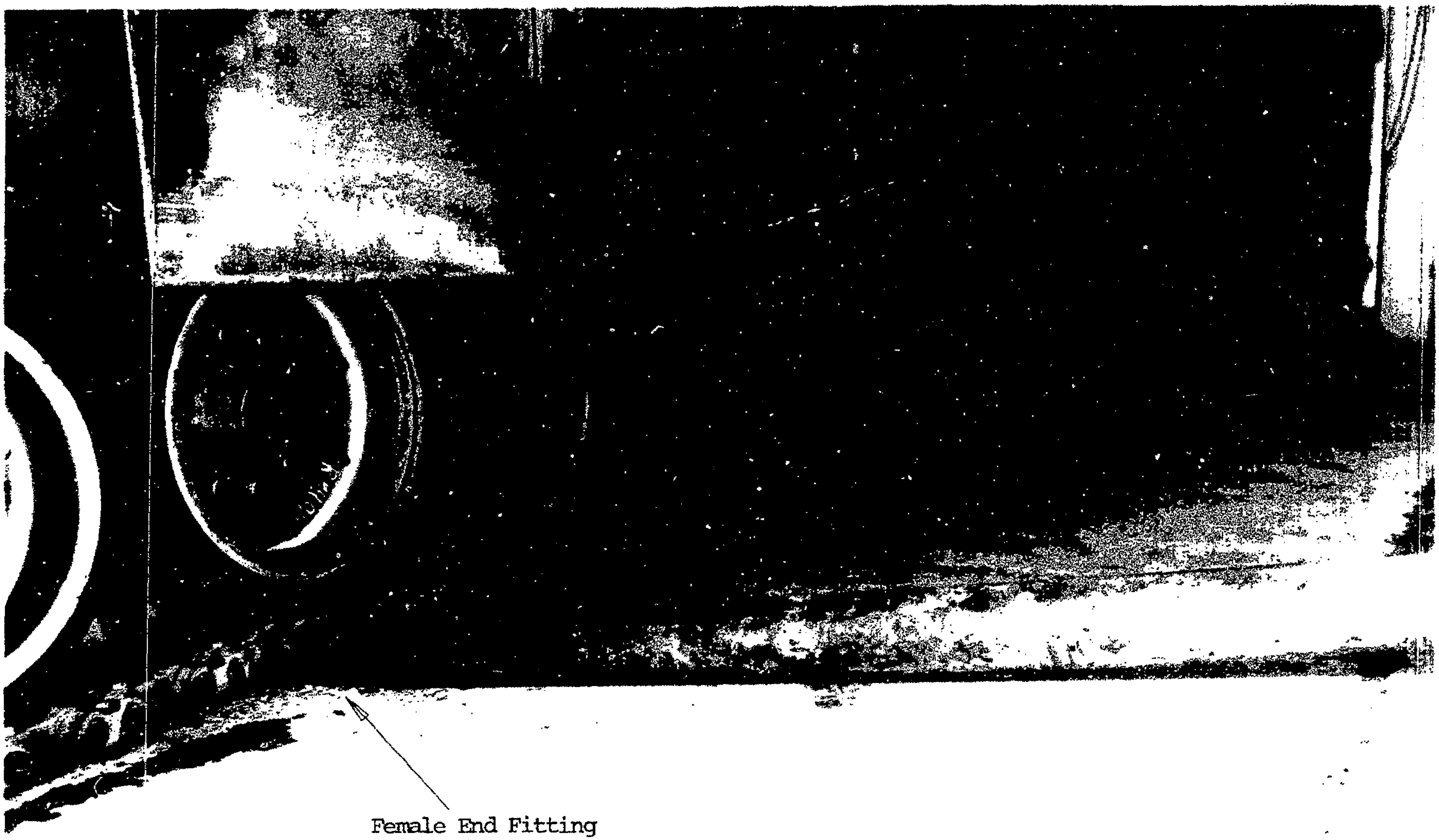

Figure 14. M1A1 running over the tube section of a tow bar leg.

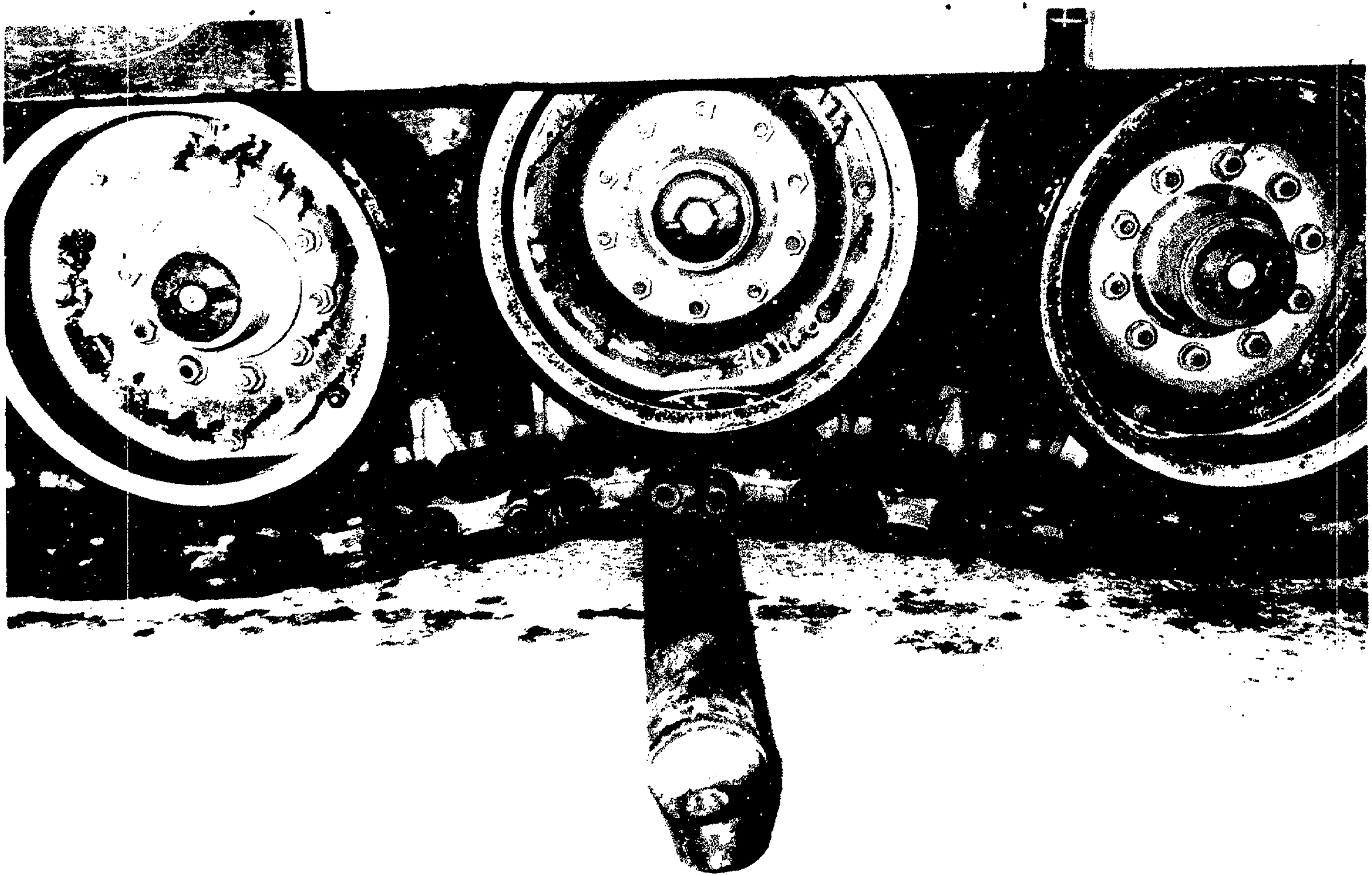

Figure 15. M1A1 running over a female end fitting.

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LABORATORY AND FIELD TESTING OF THE M1 LIGHTWEIGHT STEEL TOW BAR SYSTEM -
Christopher Cavallaro and Robert B. Dooley

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Tow bar
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In conjunction with the U.S. Army Tank-Automotive Command (TACOM), the U.S. Army Materials Technology Laboratory (MTL) has developed a lightweight steel tow bar system as an alternative to the current system used in the recovery of M1 Main Battle Tanks. The advantages of the new tow bar system are an increase in strength (by 30%), lighter weight (23% weight savings), and interchangeable legs. A series of instrumented laboratory and field tests were conducted in order to evaluate the structural integrity of this new steel tow bar system. The laboratory tests were performed in a 600,000-lb capacity tension/compression test machine at MTL. The field tests were conducted on the Perryman and Churchville Test Courses at Aberdeen Proving Ground, Aberdeen, MD. Prior to and following all tests each tow bar leg was examined for structural integrity using X-ray radiography. This nondestructive evaluation method was used to verify the success of weld penetration and identify any areas where cracks may have been induced as a result of welding or testing.

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